Analysis of segment energy transfer using musculoskeletal models in a high speed badminton stroke

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ANALYSIS OF SEGMENT ENERGY TRANSFER USING MUSCULOSKELETAL MODELS IN A HIGH SPEED BADMINTON STROKE

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1. ABSTRACT

This paper reports a combined experimental and numerical investigation of badminton stroke techniques to investigate the transfer of energy from proximal to distal segments in a whiplash type of movement. The results show rates of energy transfer that are much beyond what the involved muscles can deliver and thereby documents that significant energy is transferred via joint reaction forces in a whiplash-type motion. The results also show that positive as well as negative powers are transferred before the maximum velocity is attained.

2. INTRODUCTION

Segment energy transfer plays an important role in the performance of a wide variety of human motions. Transfer of energy between segments, and between kinetic and potential energy, is important for the economy of human walking and essential in any sport performance involving high speed movements like kicks, pitches and strokes. Many of these movements are performed at velocities that seem impossible for the human muscles to produce given their force-velocity properties, and this has attracted the attention of several scientists. Hirashima et al. investigated baseball pitching [1] and found that their results "indicate that baseball players accelerate the distal elbow and wrist joint rotations by utilizing the velocity-dependent torque that is originally produced by the proximal trunk and shoulder joint torques in the early phase." The work by Hirashima et al. is one of the recent contributions in a long row of papers investigating the kinetic chain phenomenon in which kinetic energy is concentrated toward the end of an open chain in a whiplash type of motion.

The well-known whiplash motion is characterized by a wave running from the proximal to the distal end of the whip tail while increasing its velocity. This is an interesting phenomenon because the whip is a passive structure devoid of any actuators that can perform the observed acceleration. The only forces acting between segments of the whip are section reaction forces (and possibly reaction moments to the extent the whip tail has a bending stiffness).

Contrary to a whip tail, a human arm is a discrete system comprised of rigid segments

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and articulating joints. The joints are equipped with actuators in the form of muscles, but these actuators have properties that diminish their strength as the articulation velocity increases. It is therefore likely that the motor skills behind fast strokes and pitches are based on a whiplash effect to some extent, which requires a very precise coordination.

In a discrete system, power is transferred over joints by joint moments and by reaction forces. The joint moments are generated by active muscle forces, and these moments may perform net work on the system. The reaction forces also perform work, the power of which we can quantify as a scalar product:

$$P = \mathbf{R} \cdot \mathbf{v}$$

where the 3-D vector quantities **R** and **v** are joint reaction force and joint velocity respectively. According to the third law of Newton, if the distal segment is affected by the joint reaction force **R**, then the proximal segment is affected by –**R** as illustrated in Fig. 1. Thus, the net work of the joint reaction forces is zero, but the forces transfer energy from one segment to the other.

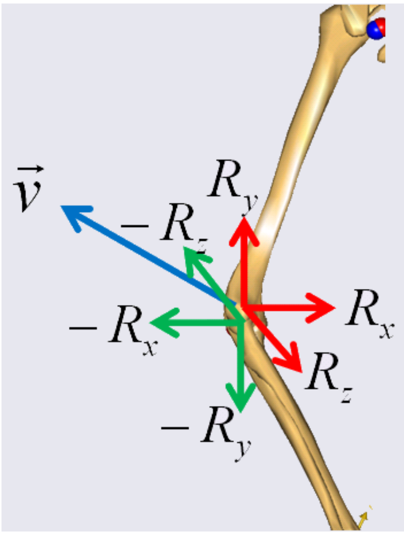

Fig. 1. Opposite joint reaction forces on proximal and distal segments.

Badminton is a fast-paced racket sport in which skilled players are capable of striking the shuttlecock with remarkable speed and precision. Racket head speeds of 135 km/h and shuttlecock exit velocities up to 200 km/h in smash strokes have been measured [2]. Furthermore, the International Badminton Federation conducts official shuttlecock speed measurements using microwave technology during championship tournaments. According to People's Daily Online [3] the world record was set by Chinese player Fu Haifeng at 332 km/h at the ninth edition of the World Mixed Team Championships.

In this paper, we perform a musculoskeletal analysis on motion capture data of an Olympic class badminton player to clarify how the players are capable of accelerating the racket to the observed speeds, and we aim to explain how segments perform work on each other and concentrate kinetic energy in the distal end of the kinetic chain at the time of impact. The insight generated is potentially valuable for coaching purposes and for understanding the joint injury mechanisms that are prevalent in several sports relying on strokes and pitches.

The challenges of the investigation arise from the fact that very fast motions are difficult to measure reliably. Furthermore, the forces in the system are due to accelerations, which are computed as second derivative of measured positions, and each step of the differentiation process tends to amplify the errors by an order of magnitude.

3. METHODS

The subject was an Olympic class badminton player who was asked to smash a shuttlecock with maximal effort.

A motion capture experiment was performed with a Qualisys Oqus 300 system comprising eight cameras sampling at a frame rate of 500 Hz. Reflective markers were attached to the arm and the racket as shown in Fig. 2.

Fig. 2. Setup of motion capture experiment. Markers are places at upper and lower sternum, T12, acromion, lateral and medial humeral epicondyles, lateral and medial wrist, the butt end of the racket handle, four markers at the distal end of the handle, and three markers on the racket head.

The interest in segment energy transfer required subsequent kinetic analysis, which relies heavily on accelerations derived from the motion capture data. The high velocities in the experiment made the necessary data processing a challenging task, and a newly developed method [4] for handling of redundant kinematics and parameter identification (Andersen et al, 2010) was employed to obtain reliable results. Marker data were imported through a zero-phase, fourth order Butterworth filter with a cutoff frequency of 15 Hz.

The data analysis was performed with the AnyBody Modeling System version 4.1 and allowed for analysis of the work performed by muscles as well as by joint reaction forces between the segments. Fig. 3 shows the musculoskeletal model in which the muscles are represented as simple torque providers in the joints.

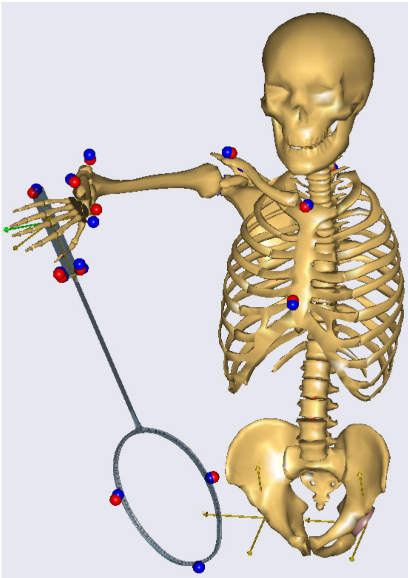

Fig. 3. Musculoskeletal model of the motion capture experiment.

4. RESULTS

The data analysis initially reveals that the racket is accelerated very abruptly just before the time of impact and decelerated abruptly right after impact as illustrated in Fig. 4.

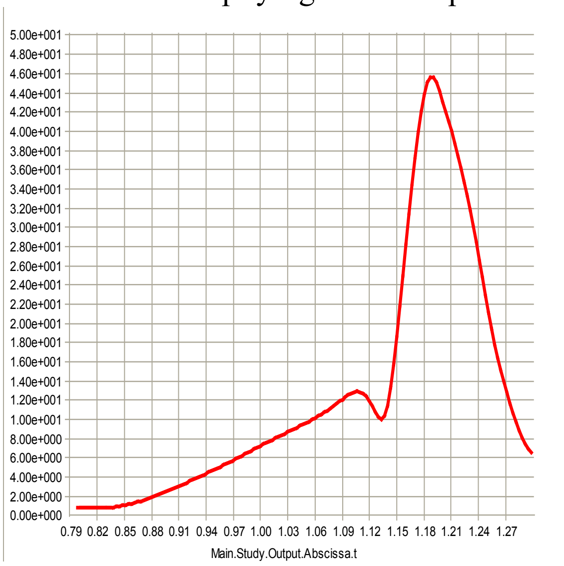

Fig. 4. Velocity [m/s] of the racket head over the stroke time [s]. The maximum velocity of 46 m/s = 165 km/h occurs at impact (t=1.19 s).

The kinetic analysis computes the power exchanged by reaction forces between the segments as illustrated in Fig. 5.

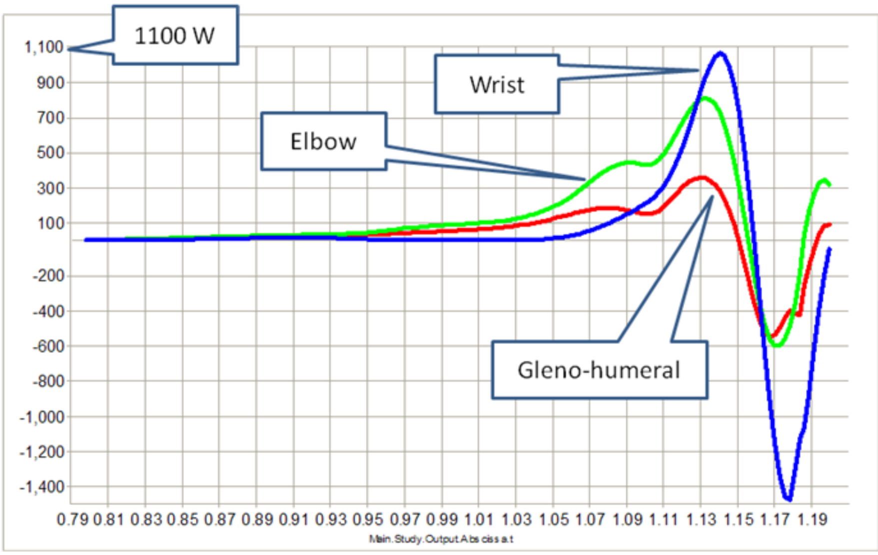

Fig. 5. Exchange of power [W] from the proximal to the distal segments at the three joints, gleno-humeral joint, elbow and wrist over the stroke time [s].

5. DISCUSSION

The kinematic results (Fig. 4) confirm that the racket head is accelerated to a high velocity at impact. Our measurement of 46 m/s exceeds previously reported results [2], which may be due to a higher frame rate used in our experiment or due to the skill of the test subject. It is interesting that the majority of the peak velocity is not built up gradually over the stroke but rather in a small time frame of only 0.04 s just before the impact. This phenomenon is also been observed in other sports like javelin throwing [5].

Fig. 5 reveals that the abrupt acceleration of the racket requires transfer of a high amount of power over the involved joints, and primarily so over the wrist joint, where the peak power exceeds 1 kW for a brief period of time. We can conclude with high certainty that this power is not generated by the muscles crossing the wrist but must be transferred between segments by the work of the reaction forces.

Fig. 5 also shows that the peak powers transferred over the joints have a proximal-to-distal nature in the sense that the gleno-humeral joint peaks first, subsequently the elbow, and finally the wrist. The proximal-to-distal sequence has been investigated a repeatedly in overarm throwing where the goal is to release a ball with maximum velocity, i.e. [1] and [6]. Compared to throwing, a badminton stroke effectively has an extra segment, namely the racket. The results indicate, also in a badminton smash, a wave of kinetic energy traveling proximally to distally in the system in order to reach maximal racket head speed.

Please notice the difference in time axes between Figures 4 and 5. Fig. 5 ends just after impact at t = 1.19 s, the time at which Fig. 4 documents that the racket head velocity peaks. However, Fig. 5 shows that significant negative energy transfer over the wrist occurs in the time leading up to the impact, effectively removing kinetic energy from the racket. Since the racket head continues to accelerate during this time, we must conclude that the increased velocity of the head is more than compensated by a deceleration of the hand and handle, again creating a whiplash effect within the rigid racket body.

It is unlikely that the stroke technique of a world-class player should be far from an optimal motion pattern, and it is therefore interesting to speculate about the physical benefit of performing negative work on distal segments by the joints before impact takes place. A thermodynamic interpretation might be useful, noticing that the majority of the power transferred through the system is likely passive, i.e. stemming from energy transfer between segments rather than from muscle work. In a thermodynamic sense, concentration of energy can only be accomplished at the cost of energy converted to heat, which may be the explanation why negative work before impact is necessary to obtain the concentration of kinetic energy towards the end of the racket.

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